DETERMINATION OF LANDAU LEVEL LIFETIMES IN n-GaAs

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The lifetime of electrons in the first excited Landau level of n-GaAs is determined from a combination of measurements of far infrared cyclotron resonance induced absorption and conductivity change. Values of T_1 of the order of 10^{-8} s for densities of excited electrons of 10^{11} cm $^{-3}$ and a temperature dependence of $T^{-2.7}$ are found. An upper limit for the $N = 0$ Landau level to donor recombination time of the order of 10^{-9} s was derived from pulsed conductivity measurements.

Recently two different methods have been reported^{1,2} to determine the lifetime of electrons in the $N = 1$ Landau level in n-InSb by cyclotron resonance absorption. Gornik et al.¹ determined this lifetime from saturation absorption measurements with an optically pumped molecular laser. Müller and Gornik² used observations of the transient decay of the photoconductivity following pulsed far infrared excitation.

In this paper a new method is presented to determine the Landau level lifetime from a combination of measurements of the far infrared cyclotron resonance induced absorption and conductivity change in n-GaAs. The observed lifetimes which are of the order of 10^{-8} s for electron densities in the excited level of 10^{11} cm $^{-3}$ suggest acoustic phonon scattering as the dominant relaxation process and are consistent with upper limits determined from pulsed excitation measurements. The lifetime shows further a temperature dependence of $T^{-2.7}$ for temperature values of $T = 11$ K - 34 K. From pulsed cyclotron resonance induced conductivity measurements an upper limit of the order of 10^{-9} s for the lifetime of the $N = 0$ Landau level i.e. the recombination-time to the donor ground state is derived.

As shown in a previous paper³ the mechanism underlying the change in the conductivity under cyclotron resonance conditions can be described by a three level model (see Fig. 1). Excitation of electrons from the lowest Landau level (2) to the first excited Landau level (3) is followed by thermal equilibration of electrons from the donor ground state (1) to the depleted lowest Landau level, thus increasing the free carrier density (Δn) and therefore the conductivity. This process can be described by the following set of rate equations:

$$\begin{aligned} \frac{dn_1}{dt} &= -t_{12}^{-1}n_1 + t_{21}^{-1}n_2 \\ \frac{dn_2}{dt} &= t_{12}^{-1}n_1 - t_{21}^{-1}n_2 + t_{32}^{-1}n_3 - W(n_2 - n_3) \\ \frac{dn_3}{dt} &= W(n_2 - n_3) - t_{32}^{-1}n_3 + t_{31}^{-1}n_3 \end{aligned} \quad (1)$$

where W denotes the induced transition rate of cyclotron resonant absorption. The electrons which are excited to the $N = 1$ Landau level relax to the $N = 0$ Landau state and the donor ground state with the transition rates t_{32}^{-1} and t_{31}^{-1} respectively. The electrons occupying the lowest Landau state return to the donor ground state with the recombination rate t_{21}^{-1} and the reverse process occurs with t_{12}^{-1} . It is further assumed that $t_{31}^{-1} \ll t_{32}^{-1}$ and that at thermal equilibrium $n_3^0 = 0$.

From the steady state condition for the rate equations, i.e. $dn_i/dt = 0$, the conservation of electrons $n_1 + n_2 + n_3 = n_1^0 + n_2^0$, and the detailed balance at thermal equilibrium, $t_{12}^{-1}n_1^0 = t_{21}^{-1}n_2^0$, one can show that the absorption coefficient α is given by the following expression:

$$\alpha \equiv (n_2 - n_3) \frac{W \hbar \omega}{I} = \frac{\hbar \omega}{I} \frac{W}{1 + WT} n_2^0 \quad (2)$$

where I is the intensity of radiation at the sample, and

$$T = (2t_{12}^{-1} + t_{21}^{-1}) / t_{32}^{-1} (t_{12}^{-1} + t_{21}^{-1}) \quad (3)$$

For the relative change in the conductivity one obtains,

$$\begin{aligned} \Delta\sigma/\sigma &= \Delta n/n_2^0 = (n_2 + n_3 - n_2^0)/n_2^0 \\ &= \frac{W}{1 + WT} T_1 \frac{n_1^0}{n_1^0 + n_2^0} \end{aligned} \quad (4)$$

with $T_1 = t_{32}$. The electronic lifetime T_1 follows directly from Eq. (2), (3) and (4)

$$T_1 = \frac{\hbar \omega}{I \alpha} \frac{\Delta\sigma}{\sigma} n_2^0 \frac{n_1^0 + n_2^0}{n_1^0} \quad (5)$$

Fig. 1 : Energy level structure of the donor ground state (1) and the two lowest conduction band states (2) and (3) in a magnetic field. W denotes the radiation induced transition rate; t_{12}^{-1} , t_{21}^{-1} and t_{32}^{-1} describe the relaxation rates between the different levels.

showing that T_1 can be calculated from the relative change in the conductivity $\Delta\sigma/\sigma$, the absorption coefficient α , the carrier density n_2^0 and the number of unionized donors $n_1^0 = N_D - N_A - n_2^0$ at thermal equilibrium. $\Delta\sigma/\sigma$ was measured as a relative change in the voltage over the sample under constant current conditions; n_2^0 was determined from Hall-effect measurements as a function of temperature. The peak absorption coefficient α was calculated from the transmission data by using

$\alpha = [\ln(W'/W'') + (rW''/W')^2 - r^2]/d$, where r is the reflectance of each sample surface, d is the sample thickness and W' and W'' are the intensities off and on resonance. The samples were chosen such that $\alpha d < 1$ to minimize errors due to variation of the absorbed power within the sample.

Fig. 2 shows the values of T_1 as a function of the temperature deduced from measurements on an n-GaAs sample of the following characteristics: $n = 1.6 \times 10^{15} \text{ cm}^{-3}$, $\mu = 7610 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at $T = 300 \text{ K}$. Both the transmission and the conductivity were measured in the Faraday configuration in the temperature range from $T = 11 \text{ K}$ to 34 K and with far infrared radiation from a cw optically pumped CH_3OH laser. The output power of the CH_3OH laser of 10 mW at $\lambda = 118.8 \mu\text{m}$ was attenuated to about $10 \mu\text{W}$ at the sample. The change in the transmission of the radiation due to the cyclotron resonant absorption was detected by a liquid helium cooled Si-bolometer.

The calculated values of T_1 vary from $5 \times 10^{-8} \text{ s}$ at 11 K to 2.10^{-9} s at 34 K for numbers of excited carriers from $n_3 = 1.1 \times 10^{11} \text{ cm}^{-3}$ to $n_3 = 0.12 \times 10^{11} \text{ cm}^{-3}$ respectively and show a temperature dependence of $T^{-2.7}$

(See Fig. 2). The magnitude of the observed lifetime and its temperature dependence suggest acoustic phonon scattering as the dominant relaxation process^{2,4,5}.

From the steady state analysis of the three level model it follows that the lifetimes cannot be obtained from steady state measurements. In order to get at least some quantitative experimental confirmation about these lifetimes we also measured the conductivity response of the n-GaAs sample to a far infrared pulse under cyclotron resonance conditions. The far infrared pulses at $\lambda = 118.8 \mu\text{m}$ were generated in a CH_3OH molecular laser optically pumped by a simultaneously current- and Q-switched conventional CO_2 laser. A peak power of about 10 kW and a pulse duration of 100 ns were obtained for the P(36) pump line giving rise to very strong far infrared pulses up to pressures of CH_3OH of a few Torr. A more complete description of the system will be given elsewhere⁶. The electrical scheme for detection of the pulsed conductivity change in the n-GaAs sample was similar to that used by Kohl et al.⁷ for their fast far infrared photoconductive detector and had a risetime of 2 ns .

A typical result is presented in Fig. 3 which shows the time dependency of the photoconductive response of the sample to a far infrared pulse at the cyclotron resonance field. The observed risetime of the pulse of 25 ns gives an upper limit to the generation rate t_{12}^{-1} as follows from the three level model of Fig. 1. From detailed balance at thermal equilibrium, i.e. $t_{12}^{-1} n_1^0 = t_{21}^{-1} n_2^0$, and the value of $t_{12} < 2.10^{-8} \text{ s}$ one obtains for the lifetime of the electrons in the $N = 0$ Landau level an

Fig. 2 : Temperature dependence of the electronic lifetime of the first excited Landau level in n-GaAs at 6.39 T. The solid line presents the fit to the data using $\log T_1 = -4.4 (\pm 1.2) - 2.72 (\pm 0.4) \log T$. The absolute values for the time are subject to a systematic error in the estimation of the incident far infrared power of about 50%.

upper limit of $t_{21} < 2 \cdot 10^{-9}$ s at $T = 12$ K. These values are consistent with the ones obtained by Melngailis et al.⁸ from recombinative radiation measurements and by Stillman et al.⁹ from the recombination time of impact ionized free carriers for zero magnetic field. The decay time of the observed pulse of 125 ns gives an upper limit to the effective recombination time resulting from the cascade transition $N = 1$ to $N = 0$ to donor ground state. Since $t_{21} < 10^{-9}$ s it follows that $t_{32} < 10^{-7}$ s which is not inconsistent with the results of the steady state measurements as described above.

In conclusion we have shown that a combination of measurements of the absorption coefficient and the associated conductivity change under cyclotron resonance conditions can be used to determine the electronic lifetime of the first excited Landau level in n-GaAs. Though this method has been used for temperatures from 11 K to 34 K this region can be easily extended to lower temperatures. To higher temperatures the method is limited by the condition for Landau quantization $\hbar\omega_c = \hbar eB/m^* > kT$. A principal limitation arises from the donor ionization energy since for $E_D < kT$ the donors are completely ionized and $\Delta\sigma/\sigma \approx 0$.

This method has substantial advantages over saturation absorption measurements and does not have the experimental complexity of the pulsed method. In fact saturation absorption measurements are only feasible for determination of lifetimes in highly nonparabolic materials like In-Sb, where absorption occurs only between two Landau levels. In case of the nearly parabolic conduction band of n-GaAs the Landau levels are nearly equally spaced so that saturation absorption implies continuous excitation in the Landau ladder up to the optical phonon emission energy, $E_{op} \approx 35$ meV. Lifetimes extracted from saturation absorption measurements in a parabolic material will therefore be determined by optical phonon emission.

Moreover the large number of excited carriers which are present at saturating conditions changes the relaxation mechanism from acoustical phonon- to electron-electron scattering as was shown by Gornik et al.¹ for n-InSb. The method described in this paper allows determination of electronic lifetimes at nearly thermal equilibrium conditions as was shown. The method can easily be extended to considerable deviations from thermal equilibrium by using higher intensities of the incident radiation thus allowing observations re-

Fig. 3 : Pulse shape (wavelength λ : 118.8 μm) of the photoconductive response of a n-GaAs sample. The pulse shape is independent of the magnetic field; the peak amplitude varies with magnetic field as is shown in the insert. The pulse shape gives an upper limit (determined by the measuring system) for the relevant electronic lifetimes.

lated to the hot electron effect as mentioned above.

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